

Charmonium in China: BEPCII/BESIII

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Results based on 106 M ψ' events and about 226 M J/ψ events acquired with the BESIII detector at BEPCII are reported, including a confirmation of the BESII $p\bar{p}$ threshold enhancement in $J/\psi \rightarrow \gamma p\bar{p}$, branching ratios for $\chi_{cJ} \rightarrow \pi^0 \pi^0$ and $\eta\eta$, and first measurements of the branching ratios for $\psi' \rightarrow \pi^0 h_c$ and $h_c \rightarrow \gamma\eta_c$, as well as measurements of the mass and width of the h_c . Also reported are first observations of the two photon process $\psi' \rightarrow \gamma\gamma J/\psi$ and $f_0(980) - a_0(980)$ mixing.

I. INTRODUCTION

The Beijing Electron-Positron Collider has been upgraded to a two-ring collider (BEPCII) with a design luminosity of $1 \times 10^{33} \text{cm}^{-2} \text{s}^{-1}$ at a center-of-mass energy of 3.78 GeV. It will operate between 2 and 4.6 GeV, allowing precision studies of charmonium (J/ψ , ψ' , $\psi(3770)$, η_c , χ_{cJ} , and h_c), charm (D and D_s mesons), and improved determinations of the tau mass and the hadronic cross section (R) in this energy region. Details on BESIII and BEPCII are described in Ref. [1].

During 2009, BESIII acquired a sample of 106 M ψ' events, or four times the CLEOc sample, and about 226 M J/ψ events, or about four times the BESII J/ψ sample. Results in this paper are based on these data sets.

II. h_c STUDIES

In 2005, CLEO [2] reported a measurement of the mass of the $h_c(^1P_1)$ in $e^+e^- \rightarrow \psi' \rightarrow \pi^0 h_c$, $h_c \rightarrow \gamma\eta_c$, where they used both inclusive and exclusive η_c decay events. In 2008, they repeated their analysis with 25 M ψ' events. [3] Combining results, they obtain $m(h_c)_{AVG} = 3525.2 \pm 0.18 \pm 0.12 \text{ MeV}/c^2$. [3] A precise determination of the mass is important to learn about the hyperfine (spin-spin) interaction of P wave states. Using the spin weighted centroid of the 3P_J states, $\langle m(^3P_J) \rangle$, to represent $m(^3P_J)$, they obtain $\Delta m_{hf}(1P) = \langle m(^3P_J) \rangle - m(^1P_1) = +0.08 \pm 0.18 \pm 0.12 \text{ MeV}/c^2$. This is consistent with the lowest order expectation of zero.

BESIII has measured $m(h_c)$ from the distribution of mass recoiling against π^0 s, both in inclusive $\psi' \rightarrow \pi^0 h_c$ samples and with samples tagged by the $E1$ photon from $h_c \rightarrow \gamma\eta_c$. This allows for the first time determinations of $B(\psi' \rightarrow \pi^0 h_c)$ and $B(h_c \rightarrow \gamma\eta_c)$. BESIII also measures for the first time the width $\Gamma(h_c)$. Results are shown in Table I and compared with CLEOc and theory. More detail may be found in Ref. [4].

TABLE I: BESIII h_c results compared with CLEOc and theory.

	BESIII	CLEOc [3]	Theory
$B(\psi' \rightarrow \pi^0 h_c)$	$4.58 \pm 0.40 \pm 0.50$	$4.16 \pm 0.30 \pm 0.37$	
$\times B(h_c \rightarrow \gamma\eta_c) [10^{-4}]$			
$B(\psi' \rightarrow \pi^0 h_c) [10^{-4}]$	$8.4 \pm 1.3 \pm 1.0$		$(4 - 13)$ [5]
$B(h_c \rightarrow \gamma\eta_c) [\%]$	$54.3 \pm 6.7 \pm 5.2$		41 (NRQCD) [5] 88 (PQCD) [5] 38 [6]
$m(h_c) [\text{MeV}/c^2]$	$3525.40 \pm 0.13 \pm 0.18$	$3525.20 \pm 0.18 \pm 0.12$	
$\Gamma(h_c) [\text{MeV}/c^2]$	$0.73 \pm 0.45 \pm 0.28$		1.1 (NRQCD) [5] < 1.44 @ 90% C.L. 0.51 (PQCD) [5]
$\Delta M_{hf}(1P) [\text{MeV}/c^2]$	$0.10 \pm 0.13 \pm 0.18$	$0.08 \pm 0.18 \pm 0.12$	

III. χ_{cJ} DECAYS

Because of the large ψ' sample and the large branching fractions for $\psi' \rightarrow \gamma\chi_{cJ}$, BESIII is in a good position to study both inclusive and exclusive χ_{cJ} decays. Since χ_{cJ} decays to two gluons, these decays are a good place to search for gluonium. [7] The color octet mechanism is important in these decays, [8] and measurements allow tests of theoretical models.

BESIII has studied $\psi' \rightarrow \gamma\chi_{cJ}, \chi_{cJ} \rightarrow \pi^0\pi^0$ and $\eta\eta$, where π^0 and η decay to $\gamma\gamma$. [9] Results are given in Table II and compared to CLEOc [10], the particle data tables (PDG08), [11] and theory [8]. Improved measurements will allow refinement of theory.

TABLE II: Branching fraction results for $\chi_{cJ} \rightarrow \pi^0\pi^0$ and $\eta\eta$. The last errors for BESIII and CLEOc are the branching fraction uncertainties for $\psi' \rightarrow \gamma\chi_{cJ}$. Note that CLEOc used their own $\psi' \rightarrow \gamma\chi_{cJ}$ branching fractions for their results.

Decay	χ_{c0} (10^{-3})	χ_{c2} (10^{-3})
$\pi^0\pi^0$	BESIII [9]	$3.23 \pm 0.03 \pm 0.23 \pm 0.14$
	CLEOc [10]	$2.94 \pm 0.07 \pm 0.32 \pm 0.15$
	PDG08 [11]	2.43 ± 0.20
	Theory [8]	2.3
$\eta\eta$	BESIII [9]	$3.44 \pm 0.10 \pm 0.24 \pm 0.20$
	CLEOc [10]	$3.18 \pm 0.13 \pm 0.31 \pm 0.16$
	PDG08 [11]	2.4 ± 0.4
	Theory [8]	3.2

BESIII is studying $\psi' \rightarrow \gamma\chi_{cJ}, \chi_{cJ} \rightarrow \gamma V$, where V is $\phi \rightarrow K^+K^-$, $\rho \rightarrow \pi^+\pi^-$, or $\omega \rightarrow \pi^+\pi^-\pi^0$. Invariant mass distributions of the high energy gamma and V are shown in Fig. 1, where clear signals for $\chi_{c1} \rightarrow \gamma V$ are observed. Preliminary results are given in Table III and compared to CLEOc [12] and perturbative QCD predictions, [13] which for $\chi_{c1} \rightarrow \gamma V$ are an order of magnitude too low. BESIII observes $\chi_{cJ} \rightarrow \gamma\phi$ for the first time.

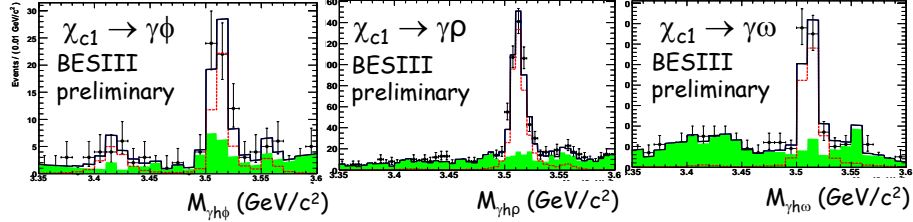


FIG. 1: Invariant mass distributions of the high energy gamma and V from $\psi' \rightarrow \gamma\chi_{cJ}, \chi_{cJ} \rightarrow \gamma V$, where V is ϕ , ρ , or ω . Dots with error bars are data, the shaded histogram is background estimated from Monte Carlo simulation, and the open black histogram is the fit. Clear signals for $\chi_{c1} \rightarrow \gamma V$ are observed.

BESIII has also fit the helicity angle distributions in the decays $\chi_{c1} \rightarrow \gamma V$. The helicity angle is the angle between the V direction in the χ_{c1} rest frame and a daughter meson in the vector meson rest frame (ρ or ϕ) or the normal to the decay plane in the ω rest frame. Longitudinal (transverse) polarization exhibits a $\cos^2\theta$ ($\sin^2\theta$) dependence. Results for f_t , where

$$f_t = \frac{N_t}{N_t + R * N_l}, \quad (1)$$

N_t is the number of fitted transversely polarized events, N_l is the number of fitted longitudinally polarized events, and R is the ratio of the efficiencies for transversely and longitudinally polarized events, are given in Table IV, along with results from CLEOc. [14] The helicity distributions indicate that the vector mesons are preferentially longitudinally polarized.

TABLE III: Branching fraction results for $\chi_{cJ} \rightarrow \gamma V$, where V is a ϕ , ρ , or ω . For BESIII, results are preliminary, and errors are statistical only.

Decay	BESIII (10^{-6})	CLEOc [12] (10^{-6})	pQCD [13] (10^{-6})
$\chi_{c0} \rightarrow \gamma\phi$	< 14.8	< 6.4	0.46
$\chi_{c1} \rightarrow \gamma\phi$	27.3 ± 5.5	< 26	3.6
$\chi_{c2} \rightarrow \gamma\phi$	< 7.8	< 13	1.1
$\chi_{c0} \rightarrow \gamma\rho^0$	< 9.5	< 9.6	1.2
$\chi_{c1} \rightarrow \gamma\rho^0$	241 ± 14	$243 \pm 19 \pm 22$	14
$\chi_{c2} \rightarrow \gamma\rho^0$	< 19.7	< 50	4.4
$\chi_{c0} \rightarrow \gamma\omega$	< 11.7	< 8.8	0.13
$\chi_{c1} \rightarrow \gamma\omega$	73.5 ± 7.6	$83 \pm 15 \pm 12$	1.6
$\chi_{c2} \rightarrow \gamma\omega$	< 5.8	< 7.0	0.5

TABLE IV: Results of fits to helicity angle distributions in $\chi_{c1} \rightarrow \gamma V$. BESIII results are preliminary.

Decay	f_t -BESIII	f_t -CLEOc [14]
$\chi_{c1} \rightarrow \gamma\rho$	$0.155 \pm 0.033 \pm 0.014$	$0.072^{+0.046+0.002}_{-0.035-0.022}$
$\chi_{c1} \rightarrow \gamma\omega$	$0.240^{+0.091+0.044}_{-0.086-0.027}$	$0.32^{+0.27+0.10}_{-0.19-0.19}$
$\chi_{c1} \rightarrow \gamma\phi$	$0.27^{+0.13+0.08}_{-0.12-0.08}$	

IV. $\psi' \rightarrow \gamma\gamma J/\psi$

Two photon transitions are well known in excitations of molecules, atomic hydrogen, and positronium but except for the discrete transitions $\psi' \rightarrow \gamma\chi_{cJ}$, $\chi_{cJ} \rightarrow \gamma J/\psi$ have never been observed in charmonium systems. BESIII has searched for continuous two photon transitions using $\psi' \rightarrow \gamma\gamma J/\psi$, $J/\psi \rightarrow l^+l^-$ events, where l is e or μ . Selection requirements are used to reduce backgrounds from $\psi' \rightarrow \gamma\chi_{cJ}$, $\chi_{cJ} \rightarrow \gamma J/\psi$ and $\psi' \rightarrow \pi^0 J/\psi$ and $\eta J/\psi$. The invariant mass distributions of the two leptons for selected events are shown in Fig. 2. A clear excess is seen at the J/ψ peak over ψ' background from Monte Carlo simulation plus continuum background. Branching fractions of $B(\psi' \rightarrow \gamma\gamma J/\psi)$ of $(1.06 \pm 0.08) \times 10^{-3}$ and $(0.99 \pm 0.07) \times 10^{-3}$ are determined for the $J/\psi \rightarrow ee$ and $J/\psi \rightarrow \mu\mu$ cases, respectively. Combining, we determine $B(\psi' \rightarrow \gamma\gamma J/\psi) = (1.02 \pm 0.05^{+0.19}_{-0.20}) \times 10^{-3}$. This is a first measurement. The result is preliminary, and more details can be found in Ref. [15].

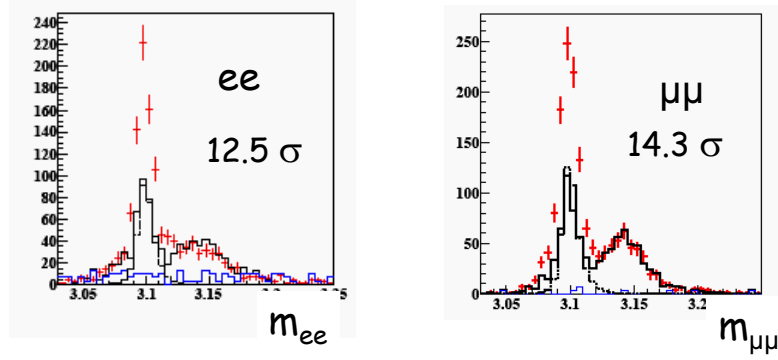


FIG. 2: Invariant mass distributions of e^+e^- and $\mu^+\mu^-$ in $\psi' \rightarrow \gamma\gamma J/\psi$, $J/\psi \rightarrow l^+l^-$ events. Dots with error bars are data. The solid black histogram is the sum of ψ' background processes from Monte Carlo simulation and background from continuum. A clear excess is seen at the J/ψ peak.

V. $f_0(980) - a_0(980)$ MIXING

The $f_0(980)$ and $a_0(980)$ are controversial particles. They have been described as $q\bar{q}$ or $q\bar{q}q\bar{q}$ states, $K\bar{K}$ molecules, or $q\bar{q}G$ hybrid states. Mixing was first suggested by Achasov, [16] and mixing measurements may be important to clarify the nature of these particles. There have been suggestions [17] for BESIII to search for mixing signals in $J/\psi \rightarrow \phi f_0 \rightarrow \phi a_0 \rightarrow \phi \eta \pi^0$, where the f_0 mixes to a_0 , and in the process [18] $\chi_{c1} \rightarrow \pi^0 a_0 \rightarrow \pi^0 f_0 \rightarrow \pi^+ \pi^- \pi^0$, where a_0 mixes to f_0 . The signal for the former case is shown in Fig. 3 a). The expected mixing signal is very narrow (8 MeV/ c^2) between the $K^+ K^-$ and $K_S^0 K_S^0$ thresholds (987 - 995 MeV/ c^2). Backgrounds are sideband and a wide a_0 from $J/\psi \rightarrow \gamma^*/K^* K \rightarrow \phi a_0$. Fitting to signal plus backgrounds determines 24.7 ± 8.6 mixing events or < 36.7 at the 90% confidence level (C.L.). This gives a mixing intensity $\xi_{fa} = (0.6 \pm 0.2 \pm 0.2)\%$ or $< 1.1\%$ at the 90% C.L. For the latter mixing case, we determine $\xi_{af} = (0.32 \pm 0.16 \pm 0.12)\%$ or $< 0.91\%$ at the 90% C.L. Figure 3 b) shows our results and upper limits compared to models ($q\bar{q}$, $q^2\bar{q}^2$, $K\bar{K}$, and $q\bar{q}g$) and calculated values (SND, KLOE, BNL, and CB) based on f_0 and a_0 parameters. References for models and calculations may be found in Refs. [17] and [18]. Ours are the first direct measurements.

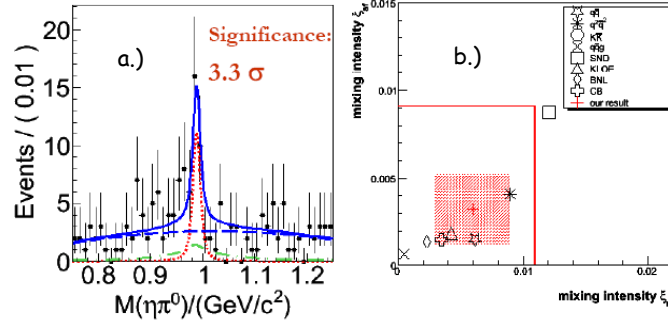


FIG. 3: a.) Invariant mass of $\eta\pi^0$ in $J/\psi \rightarrow \phi f_0 \rightarrow \phi a_0 \rightarrow \phi \eta \pi^0$. The mixing signal is very narrow (< 8 MeV/ c^2). b.) Mixing intensity ξ_{fa} versus ξ_{af} for various models and calculations and our results (shaded square) and upper limits (lines).

VI. $X(1860)$ AND $X(1835)$

BESII observed a $p\bar{p}$ threshold enhancement in $J/\psi \rightarrow \gamma p\bar{p}$. [19] Fitted to a S -wave resonance, it gives a mass below $p\bar{p}$ threshold of $M(p\bar{p}) = 1859_{-10-25}^{+3+5}$ MeV/ c^2 . BESIII has confirmed this observation [20] in $\psi' \rightarrow \pi^+ \pi^- J/\psi$, $J/\psi \rightarrow \gamma p\bar{p}$ with a fitted mass of $M(p\bar{p}) = 1861_{-13-26}^{+6+7}$ MeV/ c^2 and directly in $J/\psi \rightarrow \gamma p\bar{p}$ with a fitted mass of $M(p\bar{p}) = 1859 \pm 0.8$ (preliminary and statistical error only), shown in Fig. 4 a). CLEOc also observes a $p\bar{p}$ threshold enhancement in $\psi' \rightarrow \pi^+ \pi^- J/\psi$, $J/\psi \rightarrow \gamma p\bar{p}$ and obtains a consistent fitted mass. [21]

BESII also observed a resonance at $M(\eta' \pi^+ \pi^-) = 1833.7 \pm 6.1 \pm 2.7$ MeV/ c^2 in $J/\psi \rightarrow \gamma \eta' \pi^+ \pi^-$ where $\eta' \rightarrow \pi^+ \pi^- \eta$ and $\gamma\rho$. [22] BESIII also confirms this observation with a mass of $M(\eta' \pi^+ \pi^-) = 1842.4 \pm 2.8$ (preliminary and statistical error only), as shown in Fig. 4 b).

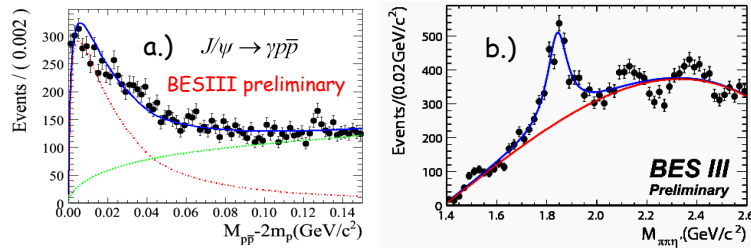


FIG. 4: a.) Threshold enhancement in $p\bar{p}$ mass in $J/\psi \rightarrow \gamma p\bar{p}$ b.) $\eta' \pi^+ \pi^-$ mass distribution in $J/\psi \rightarrow \gamma \eta' \pi^+ \pi^-$ where $\eta' \rightarrow \pi^+ \pi^- \eta$ and $\gamma\rho$.

VII. SUMMARY AND FUTURE PROSPECTS

Many results, many preliminary, have been presented based on BESIII samples of 106 M ψ' and about 226 J/ψ events. Many more results are to be expected in the future. In addition, BESIII acquired nearly $1fb^{-1}$ of data at the $\psi(3770)$ resonance this year, including approximately $75pb^{-1}$ of scan data around the $\psi(3770)$ peak. Decays of the $\psi(3770)$ produce quantum correlated $D\bar{D}$ pairs, which are ideal for mixing and CP violation studies, as well measurements of absolute branching fractions and studies of semi-leptonic decays. This sample allows BESIII to begin their charm physics program.

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